Federal Aviation Administration

DOT/FAA/AM-05/25
Office of Aerospace Medicine
Washington, DC 20591

Examining ATC Operational Errors Using the Human Factors Analysis and Classification System

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December 2005

Final Report

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-05/25		

4. Title and Subtitle	5. Report Date
Examining ATC Operational Errors Using the Human Factors Analysis and Classification System	December 2005
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Scarborough A, Bailey L, Pounds J	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
FAA Civil Aerospace Medical Institute P.O. Box 25082 Oklahoma City, OK 73125	11. Contract or Grant No.
12. Sponsoring Agency name and Address	13. Type of Report and Period Covered
Office of Aerospace Medicine Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591	14. Sponsoring Agency Code

15. Supplemental Notes

Work was accomplished under approved task AM-B-06-HRR-524

16. Abstract

In the literature of aviation accidents and incidents, human error has been recognized as the predominant factor contributing to aviation mishaps. Consequently, a number of human error models and taxonomies have been adapted to study the unique characteristics of flying an aircraft. However, relatively few attempts have been made to apply the same tools toward understanding the human factors causes of air traffic control (ATC) operational errors (OEs). An operational error is an occurrence attributable to an element of the air traffic system in which aircraft separation minima are not maintained. As a first attempt to systematically examine the underlying human causes of OEs, we report on the results of a study that consisted of three phases: (1) conducting a literature review to identify candidate error models and taxonomies, (2) selecting an appropriate error model or taxonomy for use in the ATC environment, and (3) applying the selected error model, or taxonomy, to a subset of the items identified by the FAA as OE causal factors. The results of our study revealed that, of the models and taxonomies examined, the Human Factors Analysis and Classification System (HFACS) was the taxonomy most readily adapted for use in an initial examination of ATC OEs. Causal factor items from 5,011 OE reports were classified using the HFACS taxonomy. Most items were classified as decision errors and skill-based errors. Additional research is needed to develop a more comprehensive understanding of the factors that contribute to ATC decision errors and skill-based errors.

17. Key Words	18. Distribution Statement
Air Traffic Control, Operational Errors, Human Error	Document is available to the public through the Defense Technical Information Center, Ft. Belvior, VA 22060; and the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	35	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

The authors thank Carol Manning, Ph.D., for her patience as this paper evolved and Scott Shappell, Ph.D., for his unrelenting support for this manuscript. Our air traffic experts, Don Ellis and Roger Becker, were invaluable sources of ATC information. Without their subject-matter expertise and their patience this report could not have been written. Kathy Wade and Roni Anderson, the Civil Aerospace Medical Institute's great library staff, were very patient with us during the literature search process. Finally, the authors appreciate the improvements to this manuscript suggested by our other reviewers.

EXAMINING ATC OPERATIONAL ERRORS USING THE HUMAN FACTORS ANALYSIS AND CLASSIFICATION SYSTEM

INTRODUCTION

The Federal Aviation Administration (FAA) is charged with maintaining the National Airspace System (NAS)—a vast and increasingly complex transportation system. Highly skilled air traffic control specialists (ATCSs) interact with a matrix of radars, computers, and communication systems to ensure the safe and efficient operation of aircraft. ATCSs follow established rules and procedures to separate aircraft; when separation is not maintained an operational error (OE) is recorded. OEs are defined as:

> An occurrence attributable to an element of the air traffic system in which: (1) less than the applicable separation minima results between two or more aircraft, or between an aircraft and terrain or obstacles (e. g. , operations below minimum vectoring altitude (MVA); equipment / personnel on runways), as required by FAA Order 7110. 65 or other national directive; or (2) an aircraft lands or departs on a runway closed to aircraft operations after receiving air traffic authorization. (3) an aircraft lands or departs on a runway closed to aircraft operations, at an uncontrolled airport and it was determined that a NOTAM regarding the runway closure was not issued to the pilot as required (pg. 5-1, FAA Order 7210. 56).

This report summarizes the findings of a study to examine the underlying human causes associated with ATC OEs. The study involved three phases. First, a literature search was conducted to identify aviation-related human error models and taxonomies. Second, candidate error models and taxonomies were evaluated to determine their relative strengths and weaknesses regarding their application to ATC OEs. Third, the selected candidate was used to examine the items reported as causal factors on archival OE reports. We hoped that this method would help to clarify the underlying human errors in OEs.

This study supports the FAA's National Aviation Research Plan for developing enhanced measures of human performance and increasing the understanding of factors that lead to performance decrements (FAA, 1999a). It also supports the FAA's Strategic Plan to eliminate accidents and incidents caused by human error (FAA, 1999b). In addition, this study is responsive to the Safety Strategic Objective identified in the DOT Strategic Plan for 2003-2008 (DOT, 2003) and the FAA's Flight Plan for 2004-2008 (FAA, 2003) to reduce operational errors and runway incursions.

BACKGROUND

The FAA's air traffic control (ATC) safety program relies on the timely and accurate recording and transmission of data about incidents in the U. S. airspace that "adversely affect the capabilities of ATC facilities to provide safe, orderly, and expeditious movement of air traffic" (FAA Form 7210-3, 2002, p. 4-1). To achieve these results, the FAA established a means for documenting these data. For instance, when established separation standards are not maintained, OEs are reported to the FAA's Air Traffic Service Office of Evaluations and Investigations (AAT-20). The existing process for investigating human performance factors associated with OEs involves a voluminous amount of descriptive data but provides little information about the underlying causes and remedies (Pounds & Scarborough, 2000).

We conducted a literature review to identify human error models and taxonomies that captured important elements of the cognitive processes of the human operator, the actions of the operator, and the environment in which the operator performs. These three domains extended from the earlier work of Lewin's (1951) field theory in which a person's behavior (i. e. , task performance) was postulated to be a function of the qualities of both the person and environment in which the behavior occurred.

In conducting the literature review, it became clear that the use of the term "model" and "taxonomy" sometimes were used interchangeably. However, for the purpose of this review, a taxonomy is defined as a classification system that organizes data into meaningful categories (Kirwan, 1992). In contrast to a taxonomy, a model not only describes the categories within the system, but it also indicates the manner by which the various components are affected by each other (Shorrock, Kirwan, Isaac, Anderson, & Bove, 1999). While a taxonomy has descriptive power, a model has both descriptive and predictive power. This distinction will be used later when evaluating the strength and limitations of a given model or taxonomy.

Review of Human Error Models and Taxonomies

Our literature review was focused on identifying aviation-related human error models and taxonomies that could be applied to the ATC environment. A search of six aviation technical report databases was conducted to identify the relevant literature. The six databases included: (1) the European Organization for the Safety of Air Navigation Report Database, (2) the Aviation Research

Laboratory Institute of Aviation Report Database, (3) the W. J. Hughes Technical Center Reports Database, (4) the Civil Aerospace Medical Institute (CAMI) Technical Report Database, (5) the National Aeronautics and Space Administration (NASA) Technical Report Database, and (6) the National Transportation Safety Board (NTSB) Report Database. From these sources, articles and book chapters were reviewed to determine if a given human error model or taxonomy was described in sufficient detail so that an independent analysis could be made on the relative strengths and limitations associated with an operator's: (1) cognitive process, (2) task-related behaviors, and (3) environmental conditions (i.e., organizational context).

Ten candidate taxonomies/models were selected, based on the completeness with which they addressed each of the three categories listed above (See Table 1). The authors rated the ten candidates on eight dimensions adapted from Kirwan (1992) that were designed for evaluating human error taxonomies (See Table 2). The eight dimensions included: comprehensiveness, accuracy, consistency, theoretical validity, auditability, resource usage, utility, and acceptability. Each of the dimensions and the corresponding rating scale that we developed are described in the following section. It should be mentioned that although the work of Kirwan (1992) was used as a guide, considerable adjustments were made to the definitions and rating scales to reflect the specific needs of this project.

Evaluating Human Error Models and Taxonomies

Comprehensiveness refers to the extent to which a content domain is sampled. In this project, the three domains of interest reflected an operator's: (1) cognitive process, (2) task-related behaviors, and (3) environmental conditions, such as organizational context and external factors (e.g., government regulations). A three-point rating scale was derived for judging the degree to which each of the three domains was adequately sampled by a model or taxonomy. Since the authors were not experts in the field of human error theory, they relied on the rationale presented in the source documents for justifying the domain sampling. A value of "1" meant that a rationale was presented for only one dimension (e.g., person), a value of "2" meant that a rationale was presented for two dimensions (e.g., person and task), and a value of "3" meant that a rationale was presented for all three dimensions (i.e., person, task, and environment).

Accuracy assesses the degree to which critical operator errors are captured by the error model or taxonomy. Since error reduction was the goal of this program of research, it is important that the criteria by which error reduction are judged are clearly identified. Three factors were selected for rating accuracy: the identification of system errors (such as those detected at the level of the National Airspace System), the identification of operator errors (such as the errors committed by a given ATCS), and an empirical validation that the operator errors affected the system errors (such as how the number of ATC OEs affect the system outcomes of safety efficiency and/or effectiveness). A three-point rating scale was employed to indicate the presence of one, two, or all three factors.

Consistency refers to the degree to which different users of the model or taxonomy arrive at the same results when evaluating the same material (i.e., accident reports). In statistical terms consistency as used here is associated with inter-rater agreement. However, before inter-rater agreement can be assessed, it is important that the categories of the model or taxonomy are unambiguous and mutually exclusive. Once again, a three-point hierarchical rating scheme was employed to assess consistency: A "1" was assigned when mutually exclusive categories were defined, a "2" was assigned when an empirical measure of inter-rater agreement was provided for a single study, and a "3" was assigned when empirical measures of inter-rater agreement were provided across multiple studies using different raters. It should be noted that since this dimension is associated with the calculation of a statistic, all things being equal, the error model or taxonomy with the highest measure of inter-rater agreement would be chosen.

Theoretical validity, as used here, addresses the three phases of theory development: description, prediction, and explanation (Kaplan, 1964). In the description phase, the phenomenon of interest is defined in a way that allows measurement. Given that error taxonomies are developed for the purpose of identifying error types and tracking changes across time, taxonomies tend to reside within the descriptive phase of theory development. The prediction phase is associated with identifying important variables that predict the criterion of interest. This requires that both the predictor and criterion are operationally relevant. Given that models propose a casual sequence, they are well suited for a test of their predictive validity.

The last phase of theory development deals with the power of a theory to explain why the phenomenon occurs (i.e., an empirical validation of the causal chain of events). However, instead of using just words, when an error occurs the theory can be used to explain both the necessary and sufficient conditions surrounding the event. By necessary, we mean that when the elements of the predictors (i.e., hypothesized causes) are absent, the criterion of interest -errors- is also absent. By sufficient, we mean that when the elements of the predictors are present, the criterion of interest is also present (Swartz, 1997). Since it is difficult to manipulate variables in an operational environment, theoretical validity at the

Table 1. Error Models and Taxonomies.

Name	Source	Description
Error Taxonomy		
Human Factors Analysis and Classification System (HFACS)	Wiegmann & Shappell (2003)	Identifies and organizes latent errors using a hierarchical structure involving organizational influences, unsafe supervisory actions, preconditions for unsafe acts, and unsafe acts.
Violation Taxonomy	Mason (1997)	Identifies the main organizational factors which might promote violations, and management strategies that could help to eliminate or reduce these factors by addressing the motives behind them.
A Human Error Taxonomy based on Cognitive Engineering & Social & Occupational Psychology	Bagnara et al. (1991)	Identifies four categories of conditions affecting the state of a human system: human performances, decision making, socio-organizational conditions, and external situations.
Latent Error Model of Accident Causation	Reason (1990)	Identifies four fundamental elements of all organizations that must work together harmoniously if efficient and safe operations are to occur: corporate decision makers, line management, psychological precursors of unsafe acts, and unsafe acts. Within each of the elements are latent (hidden) and active failures that represent vulnerability points for the creation of unsafe acts.
Taxonomy for Describing Human Malfunctions	Rasmussen (1986)	Identifies factors that shape performance, the contextual factors associated with error, characteristics of the task being performed, and the classification of error modes.
Pyramid Model	Isaac (1995)	Classifies human error within an air traffic management environment, composed of three levels: the top level (representing individual factors), the middle level (representing task characteristics), and the bottom level (representing the organizational influences).

(Continued)

Table 1. Continued

Name	Source	Description
Error Model		
Aviation Safety and Human Reliability Analysis Method (ASHRAM)	Miller and Forester (2000)	Allows aviation researchers to analyze aviation mishaps that involve human errors in ways that account for the operational context, crew expectations, training, airframe-related human-system interfaces, and crew resource management.
A Technique for Human Error Analysis (ATHEANA)	Cooper et al. (1996)	Performs a human reliability analysis in the context of probabilistic risk assessment. ATHEANA is based on an understanding of why human-system interaction failures occur as opposed to behavioral and phenomenological description of operator responses.
A Technique for Human Error Assessment (THEA)	Pocock, Wright, & Harrison (1999)	Used by interactive system designers and engineers to help anticipate human-machine interaction failures. The technique employs a cognitive error analysis based on an underlying model of human information processing.
A Dynamic Reliability Technique for Error Assessment in Man-Machine System (DREAMS)	Cacciabue (1993)	Identifies the origin of human errors in the dynamic interaction of the operator and the plant control system. Human error probabilities are combined with the prob-abilities of system failures in order to obtain an overall probabilistic safety assessment (PSA) for the whole plant.

Table 2. Ratings of Error Taxonomies and Models

Name	Source	Com.*	Acc.	Con.	Th.V.	Aud.	Res.	Utility	Accept.
Error Taxonomy									
HFACS	Wiegmann & Shappell (2003)	3	2	3	1	3	2	2	3
Violation Taxonomy	Mason (1997)	2	2	1	1	2	2	2	2
A Human Error Taxonomy based on Cognitive Engineering & Social &Occupational Psychology	Bagnara, et al. (1991)	2	2	1	1	2	2	2	2
Latent Error Model of Accident Causation	Reason (1990)	3	2	1	1	2	2	2	3
Taxonomy for Describing Human Malfunctions	Rasmussen (1986)	2	2	1	1	2	2	2	3
Pyramid Model	Isaac (1995)	3	2	1	1	2	2	2	1
Error Model									
ASHRAM	Miller and Forester (2000)	3	2	1	2	3	1	2	3
ATHEANA	Cooper, et al. (1996)	3	2	1	2	3	1	2	2
THEA	Pocock, Wright, & Harrison (1999)	2	2	1	2	2	1	2	2
DREAMS	Cacciabue (1993)	2	2	1	2	2	1	2	1

* Com = Comprehensiveness , Acc. = Accuracy, Con. = Consistency, Th.V. = Theoretical Validity, Aud. = Auditability
Res. = Resource Usage, Utility = Utility, Accept. = Acceptability.

explanation phase is seldom achieved in total. Using a three-point hierarchical scale, a "1" was assigned when the definitions were empirically measured, a "2" was assigned when predictive power was demonstrated, and a "3" was assigned when a causal sequence was tested for necessary and sufficient conditions.

Auditability refers to the ease by which another person can illustrate and discuss the rationale behind the results of the classifications or model predictions. It is important to note that the ratings associated with auditability were dependent on the information reported in the available literature and do not necessarily reflect the ratings that would be achieved if the authors had access to the "user" manuals. Once again, a 3-point hierarchical scale was used to assess this dimension. A rating of "1" was assigned to sources that provided just a conceptual view of an error model or taxonomy. A rating of "2" was assigned to sources that provided steps or checklists that should be followed when using a specific error model or taxonomy. A rating of "3" was assigned to sources that not only provided checklists but also incorporated examples from case histories to illustrate the kinds of judgments required of the user of a given model or taxonomy.

Resource Usage is defined by the amount of time, money, and human resources necessary to develop and maintain the infrastructure to support the error model or taxonomy. Since none of the material reviewed provided quantifiable information on resource usage, a three-point subjective scale was developed based on how much effort would be required to convert the FAA OE database so that it would be compatible with a given error model or taxonomy. The three levels included: large amount of adaptation required (rating of "1"), moderate amount (rating of "2"), and minimal (rating of "3").

Utility is based on the needs of the user. In this case, the needs of the user are two-fold, to identify and reduce the number of OEs. Utility differs from auditability in that the latter is concerned with being able to document what was done, and the former is concerned with whether what was done helped to reduce errors. A three-point scale was developed based on the ability of an error taxonomy or model to specify error reduction measures. A rating of "1" was given when errors were identified, but no guidance was provided for reducing them. A rating of "2" was used when general error-reduction guidelines were presented. Finally, a rating of "3" was used when guidelines were provided for reducing specific classes or types of errors.

Acceptability depends on how referent groups have judged the value of a given model or taxonomy. The two referent groups of interest in this study are academicians and safety practitioners. Aspects of both referent groups were integrated into a three-point hierarchical scale. A rating of "1" was given if the error model or taxonomy received a favorable review in the scientific literature about human error. A rating of "2" was granted if in addition to receiving a favorable review, the error model or taxonomy was also successfully implemented in an error reduction program within a command and control environment (e.g., a nuclear power plant or a military operations control center). If the command and control environment was aviation related, the rating was increased to a "3."

Using the above rating scheme, 4 error models and 6 error taxonomies were rated by the first two authors, as shown in Table 2. The numerical ratings associated with the 8 dimensions reflected the consensus of the authors. Although an argument could be made about any given rating, the overall trend revealed the following:

1. There was little if any variability in the ratings associated with: accuracy, consistency, auditability, and utility. Thus, each of the 10 articles included:
   a. System and operator error identification.
   b. Definitions of mutually exclusive categories (HFACS also included measured inter-rater reliability).
   c. User outline/checklist describing the steps to follow for implementing an error model or taxonomy.
   d. General error reducing guidelines.
2. Rating variability for theoretical validity and resource usage was explained by the type of technique used (i.e., error model vs. error taxonomy).
   a. All the error models had higher theoretical validity ratings when compared with all the error taxonomies. It should be noted, however, that the higher ratings for the error models was due to their potential for testing predictive validity rather than empirically demonstrating the predictive power of a given technique.
   b. All the error taxonomies were rated as requiring fewer resources to implement as compared to all the error models. Again, the source documents did not provide empirical data for direct comparisons. That being the case, the ratings reflected our best judgments based on the available materials.
3. The dimensions of completeness and acceptability were the only two dimensions whose rating variability proved to be source specific. That being the case, these two dimensions provided the most useful information with regard to selecting a given error model or taxonomy for use in a study of the underlying human factor causes of OEs.
   a. HFACS and Reason's Latent Error Model were the two highest-rated error taxonomies.
   b. ASHRAM emerged as the highest-rated error model.

Given that error models and taxonomies differed on their relative strengths and limitations, the authors decided to select one candidate from each method for further examination. HFACS was selected to represent the error taxonomies and ASHRAM was selected to represent the error models. HFACS was selected not only because of the results of Table 2 but also because its framework incorporates the work of Reason (1990) and Rasmussen (1986), both of which were highly rated taxonomies. Similarly, ASHRAM was selected because it adapted the ATHEANA model (also highly rated) for use in the aviation industry. A synopsis of both HFACS and ASHRAM is presented next.

The Human Factor Analysis and Classification System (HFACS)

The Human Factors Analysis and Classification System (HFACS; Wiegmann & Shappell, 2003) classifies human errors and the causal factors associated with them. Originally developed for aviation accidents and mishaps, HFACS has been adapted to other domains, such as mechanical and medical errors (ibid). HFACS has strong linkages to Reason's (1990) model of latent and active errors (see Figure 1) as they relate to organizational influences, unsafe supervision, pre-conditions for unsafe acts of operators (i.e., factors that affect an individual's mental and physical behavior), and the unsafe acts themselves. Active errors are related to the performance of operators in complex systems that have an immediate impact on the system, in contrast to latent (or hidden) errors of designers and managers. Whereas the active errors of the operator attract the most attention during an accident investigation, Reason (1990) noted that the latent errors of the organization, supervisor, and the preconditions of unsafe acts, may pose the greatest risk to system safety. This is because latent errors, unless they are discovered, will continue to remain in the system even after rectifying errors committed by an individual operator.

Figure 1 illustrates the concept of latent errors. Each of the four layers has "holes" (i.e., latent errors), which represent potential deficits or vulnerabilities in system safety. Under normal conditions, the holes are out of alignment, which means a deficit in one layer of the system is compensated by some protection in another layer. For example, when a pilot catches the mistake of a co-pilot or an aircraft mechanic. However, when the holes are in alignment, it means that a deficit in one layer of the system is exacerbated by a deficit in another layer. An example of multiple latent errors in alignment is a situation where a supervisor discovers that a pilot is not following the Federal Aviation Regulations (FARs) or standard operating procedures (SOPs) and elects not to do anything about it (i.e., Unsafe Supervision). The pilot continues to follow bad practices (i. e. , Precondition) until one day he commits several "Unsafe Acts" by flying under visual flight rules (VFR) into instrument meteorological conditions (IMC), that results in a controlled-flight-into-terrain (CFIT) accident.

The causal sequence depicted by the arrow in Figure 1 suggests that an unsafe act is the final failure in a series of deficits that begins at the organizational level. However, when conducting accident investigations, the starting point begins with the unsafe act committed by the operator. By asking "why" an unsafe act was committed, investigators can follow the accident chain of events through each of the four levels and uncover the direct and indirect influences on an operator's actions. As one might imagine, the discovery of latent errors requires diligent search.

Figure 2 shows how HFACS extended Reason's model by systematically identifying the vulnerability points (i.e., latent errors) at each level in the system, and then demonstrating how this analysis provided additional information about the human factor causes associated with aviation accidents. (See Wiegmann & Shappell, 2003, for a thorough description of the causal categories associated with each error level.) For instance, organizational influences are vulnerable to errors associated with resource management, organizational climate, and organizational processes. Resource management includes the management of human resources, financial allocations, equipment, and facilities. Organizational climate is broken down by its management structure, policies and procedures, and the underlying culture. Organizational processes are the operations, procedures, and safety oversight that exist within the organization.

A more complete illustration of HFACS is shown in Figure 3.

Error vulnerabilities at the supervisory level manifest themselves in the form of unsafe supervision. For example, when supervisors fail to provide guidance or accurate information to the workforce in a timely fashion, correct known problems, or willfully allow personnel to violate safety-related rules and regulations, this creates a potentially hazardous environment for the operation.

Preconditions of unsafe acts include environmental factors, personal factors, and the physical, mental, and physiological condition of the operator. Examples of the latter include physical fatigue, mental fatigue, and effects of over-the-counter medications. Whereas environmental factors represent those forces outside of the individual that affect performance (such as the weather and cockpit displays), personal factors refer to events that are brought on by the operator. These events include the use or misuse of crew resources and factors that relate to personal readiness, such as staying up late the night before an early departure.

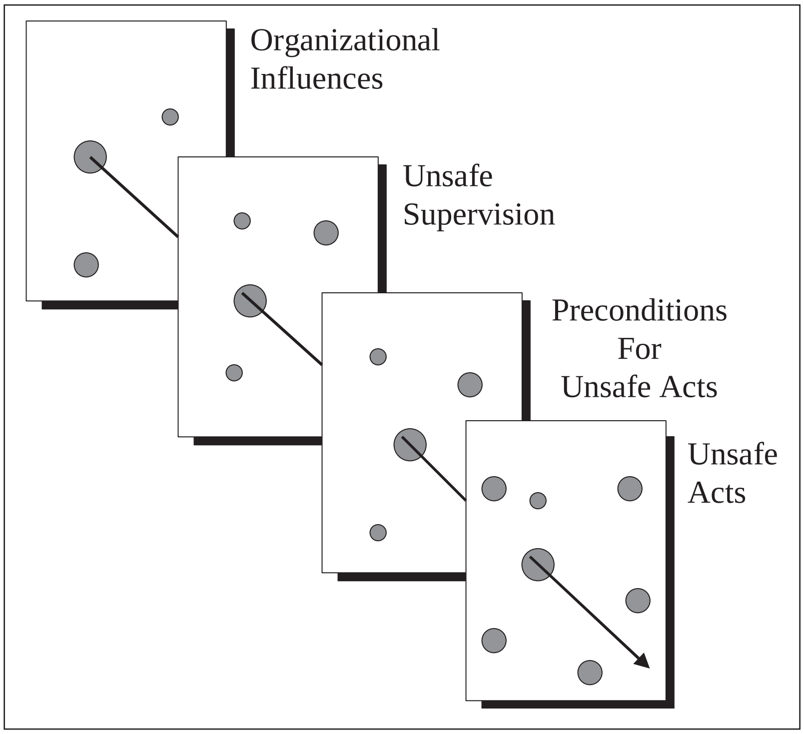

Figure 1. Reason's Latent Error Model of Accident Causation

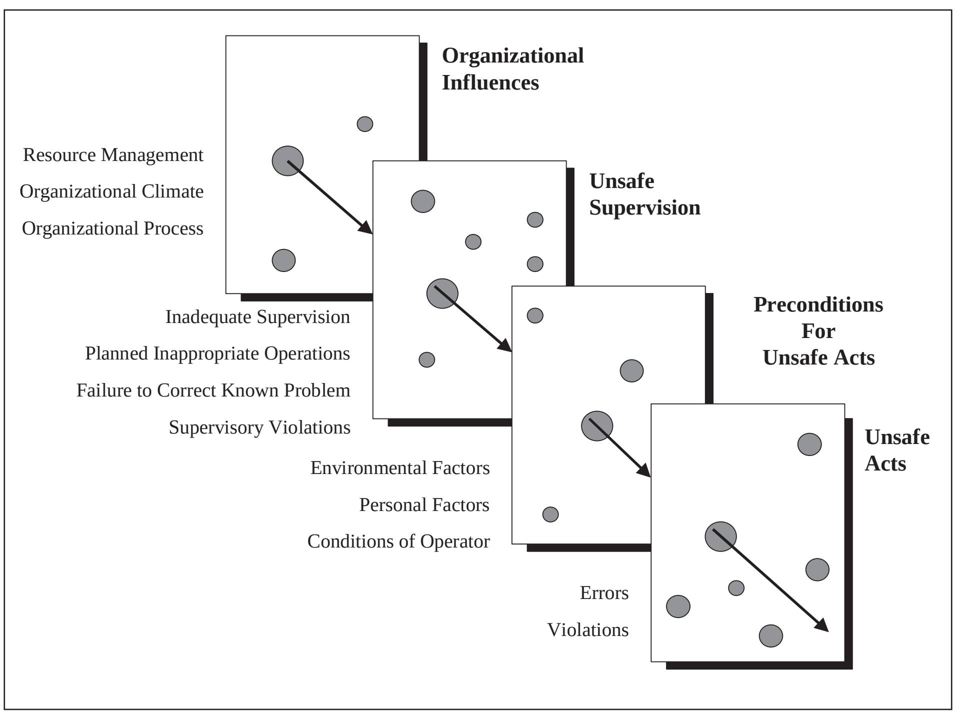

Figure 2. The Human Factors Analysis and Classification System (HFACS)
Source: Adapted from Wiegmann & Shappell (2003)

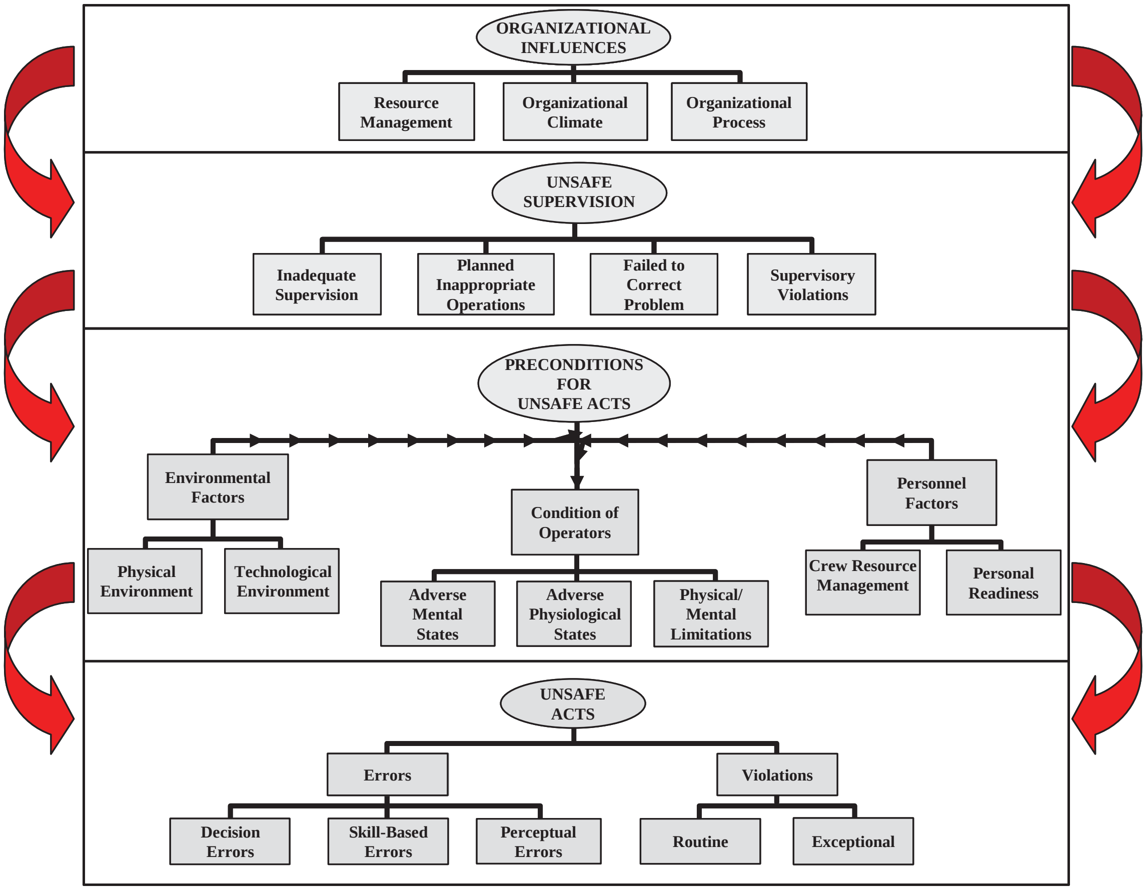

Figure 3. The Human Factors Analysis and Classification System (HFACS)

Unsafe acts are operator actions involved in producing an error. The erroneous actions are classified as either unintentional errors or willful violations. The subdivisions of unintentional errors are an adaptation of Rasmussen's Skills, Rules and Knowledge (SRK) error model (Rasmussen, 1986). The subdivisions include decision errors, skilled-based errors, and perceptual errors. In contrast to errors, violations are willful deviations from known rules and procedures. A more comprehensive overview of the HFACS categories appears in Appendix A.

Aviation Safety and Human Reliability Analysis Method (ASHRAM)

The Aviation Safety and Human Reliability Analysis Method (ASHRAM) developed by Miller and Forester (2000) belongs to a class of probability risk assessment models (PRA) that incorporates the reliability of human performance, commonly referred to as a Human Reliability Assessment (HRA). ASHRAM is an extension of A Technique for Human Error Analysis (ATHEANA) originally developed for the U. S. Nuclear Regulatory Commission (NRC). In their report on the development of ASHRAM, the authors noted that, although there were similarities between the nuclear power and aviation industries, there were enough differences to warrant the development of a HRA method unique to aviation.

The reported similarities between the nuclear power and aviation industry included:

1. Highly technological systems
2. High consequences of failure
3. Very few significant failure events
4. Governmental regulation of hardware and operations
5. Small, highly qualified crew in control
6. Simulators used in crew training
7. Dependence upon displays for information about the environment.

Differences between the two industries are shown in Table 3. Appendix B provides additional background on PRAs, HRAs, and the development of ATHEANA.

As shown in Figure 4, ASHRAM is a causal model of a pilot's cognitive processes, which consists of the error forcing context, error mechanisms, and unsafe or contributory actions. The Error Forcing Context (EFC) is divided into two categories, those that influence the pilot and those that influence the aircraft. Both types of influences serve as input to the pilot's environmental perceptions. Pilot EFCs consist of six channels of input: (1) information from maps and manuals, (2) environmental cues (i. e. , things happening outside of the aircraft) such as traffic (TF) and weather (WX), (3) data link (wireless transfer of information such as the listing of pilot reports [PIREPs] and electronic communications from air traffic control, ATC), (4) displays and controls (flight and systems instrumentation, control yoke, trim wheels, switches and cockpit computer input devices), (5) radio communications from ATC, other planes, and intercom with other crew members, and (6) verbal communications with other crew members. The design of the aircraft and the laws of physics as well as the control actions of the pilot determine aircraft EFCs.

As with ATHEANA, the basic cognitive model detailing the mechanisms of pilot error is based on the work of Woods, Johannesen, Cook, & Sarter (1994), Woods & Paterson (2000), Roth, Mumaw, & Lewis (1994), Mumaw and Roth (1992), and Reason (1990). The model consists of three classes of cognitive function that are interactive and non-sequential: (1) Environmental Perception, (2) Reasoning and Decision Making, and (3) Action. These error producing mechanisms are further augmented by operator conditions such as stress and fatigue and the training received concerning aircraft design and operating procedures.

Environmental perceptions consist of perceptual processes, attention, detection, recognition, monitoring, interpretation of environmental cues, and the overall understanding of the state of the aircraft/environmental system. Although the elements that comprise environmental perceptions are similar to the elements comprising what is commonly referred to as "situation awareness" (SA), Miller and Forester (2000) note that there is enough controversy over the definition of SA that it became necessary to avoid that term. For more information about SA and the controversy surrounding it, the reader is referred to Endsley (1995), Flach (1995), and Sarter and Woods (1991).

Reasoning and decision making, as defined by Miller and Forester (2000), is the cognitive or thinking process that includes awareness and deduction of unsafe or dangerous conditions, remembering situation-specific training, deciding to follow recommended procedures, planning flight navigation, diagnosis of trouble symptoms, deciding how to respond to situations, problem solving, and novel or creative use of existing tools or symptoms.

The pilot's actions are the control inputs to the airframe, operation of control hardware in the cockpit, communications to crew and passengers, and any other overt physical behaviors. As shown in Figure 4, these actions may produce unsafe or contributory actions.

A pilot's unsafe actions are the overt acts of commission or omission that are taken by the pilot and/or crewmembers that lead to a degradation in safety. However, Miller and Forester (2000) emphasize that the individuals involved may not know they are committing an unsafe act, and instead may be performing actions that make sense to them at the time. The latter then are referred to

Table 3. Summary of the Major Differences Between Nuclear Power and Aviation as Reported in Miller, D., & Forester, J. (2000).

Topics	Nuclear Power	Commercial Aviation
Licensing agency	NRC	Federal Aviation Administration
Potential accident consequences	Extremely High; thousands of lives	Very High; hundreds of lives
Incentives to operate w/inadequate safety	Power grid needs, profits of utility	Meet schedule, passenger frustration, airline profits
Reports of errors and near misses—human error probabilities (HEPs) available	The industry has developed an HEP databank, called NUCLARS, but participation has been minimal	There are several databases of near misses and accidents, some are privately owned by airlines, others are public—no known banks include HEPs
Contact with help in emergencies	Shift Technical Advisor, Incident team at Emergency Operations Center, Technical Evaluation Center	Radio to radar centers, tower, airlines, manufacturer
Normal operations	Continuous, mostly supervisory control, with periods of direct, manual control	Each flight is a discrete event and is dependent on crew for initiating and orchestrating. During cruise supervisory control is used.
Minimum elements needed for mission: critical functions	Fuel, cooling, pressure control, power conversion systems, crew, safety systems	Flight controls, thrust, cabin pressure or supplemental oxygen, navigation information, pilot, communication w/destination, flyable weather
Physical inertia	High, with a few notable exceptions, such as large loss-of-coolant accidents (LOCAs), changes in physics take place slowly—minutes and hours	Low, changes happen rapidly—seconds and minutes
Speed of system response	Relatively slowly, except large LOCA – slow feedback from inputs	Relatively fast—rapid feedback from inputs
Feedback from system to control inputs	Remote reports and instrumentation; mostly discrete readouts, but some integrated displays, mixture of electromechanical and electronic	"Seat-of-pants", real-time visual, aural, kinesthetic, also instrumentation; mostly discrete readouts, but some integrated displays, mixture of electromechanical and electronic
Emergency operation written guidance	Written, symptom-based procedures	"Manual decision-making," and checklists for most critical flight operations
Accident sequences	A few major decisions and actions can cover several hours	Many decisions and actions can cover only a few minutes
Transient conditions	Difficult to integrate all info to construct valid mental model	Easier to construct mental model from discrete displays
Activation of emergency subsystems	Automatic, in most cases, with crew notification	Pilots are in the loop—get warning displayed and have to initiate safety system response

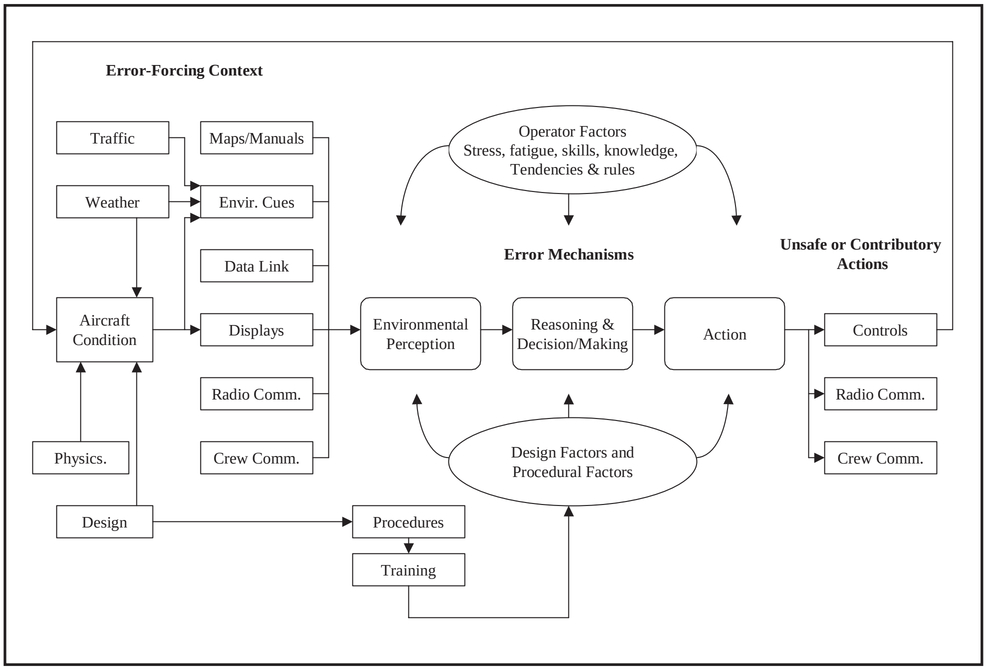

Figure 4. ASHRAM (Miller & Forester, 2000)

as contributory actions. For example, the assumption that an aircraft was running out of fuel (due to the erroneous belief that both right and left tanks had been used) may lead to a forced landing on inappropriate terrain.

Selecting and Testing the Candidate

As can be seen from the previous discussions, both HFACS and ASHRAM are well suited for the study of pilot errors. Thus, the authors chose between the two techniques based on which one (1) could be more readily used for the study of OEs and (2) would be best suited for a retrospective analysis of archival OE data. Both HFACS and ASHRAM employ retrospective analysis techniques in determining the underlying causes of human factors errors among pilots. In fact, a number of the elements associated with ASHRAM's error mechanisms shown in Figure 4 have a parallel in HFACS due to the common influence of Reason's (1990) model of human error.

In the end, the choice was based on the time it would take to develop materials from each of the two techniques for use in our study. Of the two candidates, we determined that HFACS could be used "as is." Thus, the HFACS taxonomy was selected. Later, in the discussion section, we will return to the issue of how HFACS and ASHRAM might be integrated so that an analysis could be conducted to assess risk factors associated with OEs.

METHOD

Three steps were used to study the underlying human factors causes of ATC OEs.

First, two coders were trained to use of the HFACS methodology. Second, items from the FAA's Air Traffic Control Operational Error/Deviation Report Form 7210-3 (FAA, 2002) were mapped onto HFACS categories. Third, once a reliable mapping was completed, the results were used to describe the pattern of human factors causes of ATC OEs reported for the five-year period from 1998–2002.

Coders

Two ATC SMEs were selected for their experience with operations in both terminal and en route facilities. Each SME had more than 15 years of combined ATC experience in these types of facilities. In addition, both SMEs possessed specialized knowledge about the air traffic control quality assurance process and experience in identifying the causal factors associated with OEs. Both SMEs had job-related experience using Form 7210-3 while working at ATC facilities. They also obtained HFACS experience in a previous study requiring that they use HFACS subcategories to classify narrative information from ATC OEs.

Materials

Operational Error/Deviation Report (Form 7210-3). Block 68 of Form 7210-3 lists potential OE causal factors (See Appendix C). The causal factors are divided into 6 major categories: (1) Data Posting, (2) Radar Display, (3) Aircraft Observation (Towers only), (4) Communication Error, (5) Coordination, and (6) Position Relief Briefing. Each main category is further divided into clusters of items that provide greater specification about the causal factor category. Each cluster also has an item labeled "other" but this item was not used in this study. Overall, a total of 48 items from Block 68 were used.

The Human Factors Analysis and Classification System (HFACS). Coders were provided copies of the definitions for each HFACS category and subcategories as shown in Appendix A. HFACS categories used for the classification task included unsafe operator acts, preconditions for unsafe acts, unsafe supervision, and organizational influences.

Procedures

The procedures were divided into three phases, a training phase for the SME coders, a mapping phase, and a classification phase conducted by the researchers.

Training Phase

Each SME received a blank copy of the causal factors listed on FAA Form 7210-3 in Block 68 (see Appendix C) and the HFACS categories and definitions (see Appendix A). After reviewing the materials the SMEs were asked if they needed further clarification. The SMEs were then provided with separate office space and asked to associate each item in Block 68 of Form 7210-3 with an appropriate HFACS category. Once they completed their tasks they were brought together to discuss any problems they encountered. The SMEs were provided with an opportunity to change their results before returning all material to the researchers.

Mapping Phase

One week after training, the SMEs returned to repeat the same task they accomplished during the training phase. For this activity the SMEs worked independently and were not permitted to discuss their results until they were turned in to the researcher. These procedures were necessary to calculate a measure of inter-rater agreement so that comparisons could be made with results reported in Wiegmann & Shappell (2003). After the researchers had collected the materials, any differences between the two SMEs were discussed until a consensus was reached as to the "right answer." These results were then used to conduct the classification phase.

Classification Phase

The authors constructed a Block 68 by HFACS frequency matrix using a sample of convenience consisting of 10,754 causal factors extracted from 5,011 FAA OE reports for the period 1998 to 2002. The frequencies associated with each category listed in Block 68 of Form 7210-3 were then associated with the appropriate HFACS category as identified in the mapping phase.

RESULTS

Matching Phase

Table 4 shows the results of the matching phase during which the two SME coders associated each of the 48 items from Block 68 of Form 7210-3 with a corresponding HFACS category. Coefficient Kappa was computed to test the extent to which the two SMEs agreed on their associations. The resulting kappa of .96 indicated a high level of agreement (Fleiss, 1981). This value is somewhat higher than those reported by Wiegmann and Shappell (2003). In those studies kappa ranged from a low of .60 to a high of .95.

Of the 48 Block 68 items, 62% (n=29) were associated with the HFACS subcategory of skill-based errors and 38% (n=18) were associated with the HFACS subcategory of decision errors. It is interesting to note that the SMEs were unable to find any Block 68 items that corresponded to preconditions for unsafe acts, unsafe supervision, or organizational influences. This was because there was no place on Form 7210-3 to record this information.

Table 4 also demonstrates that certain item categories from Block 68 were more often associated with a given HFACS subcategory than others. For example, most of the items comprising the data-posting category were associated with skill-based errors. In contrast, for the tower observations and position debriefings categories, the items were predominately associated with decision errors. Items in the radar display and coordination clusters had a mixed association with skill-based and decision errors.

Classification Phase

Of the 10,754 causal factors extracted from 5,011 OE reports, 1350 (13%) causal factors were listed as "other." Since no additional information was provided as to what "other" might be, this information could not be classified. Thus these data were dropped from further analyses. The remaining 9,404 causal factors were categorized according to the mapping framework identified by the SMEs in the matching task. The results are displayed in Table 5.

Table 5 is a Block 68 by HFACS category matrix in which row totals are the total number of causal factors associated with a given Block 68 category, and column

Table 4. Form 7210-3 Causal Factors and Associated HFACS Subcategories

Causal Factors	Associate HFACS Subcategories
Data Posting Category	
Computer Entry Cluster	
Incorrect input	Skill-Based Error
Incorrect update	Skill-Based Error
Premature termination of data	Decision Error
Input/Update not made	Skill-Based Error
Flight Progress Strip Cluster	
Not updated	Skill-Based Error
Interpreted incorrectly	Skill-Based Error
Posted incorrectly	Skill-Based Error
Updated correctly	Skill-Based Error
Premature removal	Skill-Based Error
Radar Display Category	
Misidentification Cluster	
Failure to reidentify aircraft when the accepted target identity becomes questionable	Skill-Based Error
Overlapping data blocks	Skill-Based Error
Acceptance of incomplete or difficult to correlate position information	Decision Error
Inappropriate Use of Displayed Data Cluster	
MODE C	Decision Error
BRITE	Decision Error
Conflict alert	Decision Error
Failure to detect displayed data	Skill-Based Error
Failure to comprehend displayed data	Skill-Based Error
Failure to project future status of displayed data	Skill-Based Error
Aircraft Observation (Towers Only) Category	
Actual Observation of Aircraft	Decision Error
Improper Use of Visual Data Cluster	
Landing	Decision Error
Taking Off	Decision Error
Ground Operation	Decision Error
Taxiing across runway	Decision Error
Holding in position for takeoff	Decision Error
Phraseology	Skill-Based Error
Transposition	Skill-Based Error
Misunderstanding	Skill-Based Error
Read-back Cluster	
Altitude	Skill-Based Error
Clearance	Skill-Based Error
Identification	Skill-Based Error
Other	
Acknowledgment	Skill-Based Error

(Continued)

Table 4. Continued

Communication Error Category	Associate HFACS Subcategories
Coordination Category	
Area of incident Cluster	
Intra-sector/position	Skill-Based Error
Inter-sector/position	Skill-Based Error
Inter-facility	Skill-Based Error
Facility type	
Failure to utilize/comply with precoordination information	Skill-Based Error
Improper use of Information Exchanged in Coordination Cluster	
Aircraft identification	Decision Error
Altitude/Flight level	Decision Error
Route of flight	Decision Error
Speeds	Decision Error
APREQs	Decision Error
Special instructions	Decision Error
Failure to Coordinate between Ground and Local Control Cluster	
Crossing active runway	Skill-Based Error
Vehicle, equipment, or personnel on active runway	Skill-Based Error
Use of other than active runway for arrival and departures	Skill-Based Error
Runway closure	Skill-Based Error
Position Relief Briefing Category	
Employee did not use position relief checklist	Decision Error
Employee being relieved gave incomplete briefing	Skill-Based Error
Relieving employee did not make use of pertinent data exchanged at briefing	Decision Error

Table 5. Frequencies of OE Causes by HFACS Subcategories*

OE Causes	HFACS Categories																
	V	PE	SBE	DE	PR	CRM	PML	APS	AMS	SV	FC	PIO	IS	OP	OC	RM	Row Total
Data Posting	0	0	556	27	0	0	0	0	0	0	0	0	0	0	0	0	**583**
Computer Entry	0	0	167	27	0	0	0	0	0	0	0	0	0	0	0	0	**194**
Incorrect input	0	0	69	0	0	0	0	0	0	0	0	0	0	0	0	0	**69**
Incorrect update	0	0	32	0	0	0	0	0	0	0	0	0	0	0	0	0	**32**
Premature termination date	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	**27**
Input/Update not made	0	0	66	0	0	0	0	0	0	0	0	0	0	0	0	0	**66**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Flight Progress Strip	0	0	389	0	0	0	0	0	0	0	0	0	0	0	0	0	**389**
Not updated	0	0	107	0	0	0	0	0	0	0	0	0	0	0	0	0	**107**
Interpreted incorrectly	0	0	186	0	0	0	0	0	0	0	0	0	0	0	0	0	**186**
Posted incorrectly	0	0	41	0	0	0	0	0	0	0	0	0	0	0	0	0	**41**
Updated incorrectly	0	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0	**44**
Premature removal	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	**11**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Radar Display	0	0	5260	250	0	0	0	0	0	0	0	0	0	0	0	0	**5510**
Misidentification	0	0	212	27	0	0	0	0	0	0	0	0	0	0	0	0	**239**
Failure to reidentify aircraft	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	**22**
Overlapping data blocks	0	0	190	0	0	0	0	0	0	0	0	0	0	0	0	0	**190**
Acceptance of incomplete information	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	**27**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Inappropriate Use of Displayed Data	0	0	5048	223	0	0	0	0	0	0	0	0	0	0	0	0	**5271**
MODE C	0	0	0	121	0	0	0	0	0	0	0	0	0	0	0	0	**121**
BRITE	0	0	0	44	0	0	0	0	0	0	0	0	0	0	0	0	**44**
Conflict alert	0	0	0	58	0	0	0	0	0	0	0	0	0	0	0	0	**58**
Failure to detect	0	0	1447	0	0	0	0	0	0	0	0	0	0	0	0	0	**1447**
Failure to comprehend	0	0	1205	0	0	0	0	0	0	0	0	0	0	0	0	0	**1205**
Failure to project future status	0	0	2396	0	0	0	0	0	0	0	0	0	0	0	0	0	**2396**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Aircraft Observation (Towers Only)	0	0	0	721	0	0	0	0	0	0	0	0	0	0	0	0	**721**
Actual Observation of Aircraft	0	0	0	277	0	0	0	0	0	0	0	0	0	0	0	0	**277**
Improper Use of Visual Data	0	0	0	444	0	0	0	0	0	0	0	0	0	0	0	0	**444**
Landing	0	0	0	141	0	0	0	0	0	0	0	0	0	0	0	0	**141**

Table 5 Continued.

OE Causes	V	PE	SBE	DE	PR	CRM	PML	APS	AMS	SV	FC	PIO	IS	OP	OC	RM	Row Total
Taking Off	0	0	0	173	0	0	0	0	0	0	0	0	0	0	0	0	**173**
Ground Operation	0	0	0	130	0	0	0	0	0	0	0	0	0	0	0	0	**130**
Taxing across runway	0	0	0	85	0	0	0	0	0	0	0	0	0	0	0	0	**85**
Holding for takeoff	0	0	0	45	0	0	0	0	0	0	0	0	0	0	0	0	**45**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Communication Error	0	0	1486	0	0	0	0	0	0	0	0	0	0	0	0	0	**1486**
Phraseology	0	0	141	0	0	0	0	0	0	0	0	0	0	0	0	0	**141**
Transposition	0	0	223	0	0	0	0	0	0	0	0	0	0	0	0	0	**223**
Misunderstanding	0	0	242	0	0	0	0	0	0	0	0	0	0	0	0	0	**242**
Readback	0	0	698	0	0	0	0	0	0	0	0	0	0	0	0	0	**698**
Altitude	0	0	382	0	0	0	0	0	0	0	0	0	0	0	0	0	**382**
Clearance	0	0	155	0	0	0	0	0	0	0	0	0	0	0	0	0	**155**
Identification	0	0	161	0	0	0	0	0	0	0	0	0	0	0	0	0	**161**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Acknowledgment	0	0	182	0	0	0	0	0	0	0	0	0	0	0	0	0	**182**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Coordination	0	0	741	220	0	0	0	0	0	0	0	0	0	0	0	0	**961**
Area of incident	0	0	457	0	0	0	0	0	0	0	0	0	0	0	0	0	**457**
Intra-sector / position	0	0	227	0	0	0	0	0	0	0	0	0	0	0	0	0	**227**
Inter-sector / position	0	0	230	0	0	0	0	0	0	0	0	0	0	0	0	0	**230**
Inter-facility	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Facility type	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Failure to utilize / comply with pre-coordination	0	0	185	0	0	0	0	0	0	0	0	0	0	0	0	0	**185**
Improper use of information	0	0	0	220	0	0	0	0	0	0	0	0	0	0	0	0	**220**
Aircraft ID	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0	0	**28**
Altitude/Flight level	0	0	0	87	0	0	0	0	0	0	0	0	0	0	0	0	**87**
Route of flight	0	0	0	46	0	0	0	0	0	0	0	0	0	0	0	0	**46**
Speeds	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	**7**
APREQS	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	**24**
Special Instructions	0	0	0	28	0	0	0	0	0	0	0	0	0	0	0	0	**28**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Ground and Local Control Failure	0	0	99	0	0	0	0	0	0	0	0	0	0	0	0	0	**99**
Crossing active runway	0	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0	**44**
Vehicle or personnel on active runway	0	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	**25**

Table 5 Continued.

OE Causes	V	PE	SBE	DE	PR	CRM	PML	APS	AMS	SV	FC	PIO	IS	OP	OC	RM	Row Total
Use of other than active runway for arrival and departures	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	**15**
Runway closure	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	**15**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Position Relief Briefing	0	0	50	93	0	0	0	0	0	0	0	0	0	0	0	0	**143**
Employee did not use checklist	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	**19**
Incomplete briefing	0	0	50	0	0	0	0	0	0	0	0	0	0	0	0	0	**50**
Relieving employee did not make use of pertinent data	0	0	0	74	0	0	0	0	0	0	0	0	0	0	0	0	**74**
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**NA**
Col.Total	**0**	**0**	**8093**	**1311**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**9404**

*HFACS Codes
V – Violations
PE – Perceptual Errors
SBE – Skilled-Based Errors
DE – Decision Errors
PR – Personal Readiness
CRM – Crew Resource Mangement
PML – Physical/Mental Limitations
APS – Adverse Physiological States
AMS – Adverse Mental States
SV – Supervisory Violations
FC – Failed to Correct Problem
PIO – Planned Inappropriate Operations
IS – Inadequate Supervision
OP – Organizational Process
OC – Organizational Climate
RM – Resource Management

totals are the total number of causal factors associated with a given HFACS category. Cell totals are the frequency with which a given Block 68 category was associated with a given HFACS category.

By examining the row totals we can see that of the 9,404 causal factors extracted, 5,510 (59%) were associated with the radar display, 1,486 (16%) were associated with communications, 961(10%) were associated with coordination, 721(8%) were associated with aircraft observation, 583(6%) were associated with data posting, and 143(1%) were associated with position relief briefings.

When the same Table 5 information is examined by column totals we see that 8,093 (86%) cases were classified as skill-based errors and 1,311 (14%) cases were classified as decision errors. It is interesting to note that these results are similar to those reported for aviation accidents. For the period 1990-2000,Wiegmann and Shappell (2003) reported that 80% of general aviation accidents involved skill-based errors and 20% involved decision errors.

The cell values shown in Table 5 represent the interaction of row and column totals for each of the six Block 68 categories. First, of the 583 data posting errors, 556 (95%) were classified as skill-based errors and 27 (5%) were classified as decision errors. Second, of the 5,510 OEs related to the radar display, 5,260 (95%) were classified as skill-based errors and 250 (5%) were classified as decision errors. Third, for OEs related to problems with the Tower controller's observation of aircraft, all 721 of them (100%) were classified as decision errors. Fourth, for OEs reported as communication errors, all 1,486 of them (100%) were classified as skill-based errors. Fifth, of the 961 OEs reported as involving coordination, 741 (77%) were classified as skill-based errors and 220 (23%) were classified as decision errors. Sixth, of the 143 OEs related to position relief briefings, 50 (35%) were classified as skill-based errors and 93 (65%) were classified as decision errors.

DISCUSSION

The goal of this project was to systematically examine the underlying human factor causes of ATC OEs. This was achieved by using the HFACS framework for the ATC environment. One of the immediate benefits from classifying OEs into HFACS categories was the realization that the majority (86%) of OEs were classified as skill-based errors and not decision errors. The ramifications of this finding affect not only the kind of training that controllers should receive following an OE, but also the expectations about the impact that ATC decision support tools will have on lowering the number and severity of OEs.

As previously discussed, skill-based errors tend to be the result of habitual actions associated with an individual's attention, memory, and/or execution technique. Rather then being executed by conscious thought, skill-based actions (along with their corresponding errors) tend to be executed with little conscious effort. From a training perspective, then, it is important to discover what skill-based actions are being executed erroneously so that the individual can be made aware of the problem. Thus, a skill-based training environment (ideally one that simulates actual job conditions) is necessary to practice new skills so that they can be executed without much conscious thought. For example, if an OE were the result of a controller's perceptual scan, then an appropriate training environment would be one that consists of scanning activities. Similarly, if a loss of memory were implicated in an OE, then an appropriate training environment would be one that consists of job-related memory activities. In both cases the training activities should provide increasing levels of difficulty until the prescribed skills are performed routinely under actual job conditions.

In contrast to skill-based errors, decision errors are the result of intentional behaviors that proceed as planned, yet the plan itself proves to be inadequate for the situation at hand. In HFACS, there are three types of decision errors: procedural errors, poor choices, and problem-solving errors; all of which require conscious effort to execute. From a training perspective, then, the challenge is to provide exercises that will improve a person's ability to make better decisions within the time constraints imposed by the job setting. For example, assume that an OE was the result of an ATCS issuing an altitude change to resolve a potential conflict, but in so doing created a loss of separation with another aircraft. After investigating the OE, it may be determined that the ATCS would benefit from real-time training activities that required him/her to predict the consequences of various actions (i.e., speed, heading, and altitude changes) used to prevent a potential loss of separation.

Although fewer causal factors were classified as decision errors than skill based errors, considerable attention has been placed on using technology to aid the controller's decision process. For example, decision support tools now exist that provide controllers with the capability of modeling the best route through a sector or within a sector so as to minimize interference with other aircraft routes in adjacent sectors and maximize the ability to detect potential conflicts. One might expect that with improved decision support tools there would be fewer OEs. It should be noted, however, that by design decision tools are directed at aiding controller decisions. Thus, the expected reduction in OEs should come from those errors that are the result of poor decisions. However, if the majority of OEs result from skill-based errors (at least based on the results found in this analysis), it would seem that greater attention should be placed in this area.

One area of training that has recently been developed to improve ATC skills is entitled The National Air Traffic Professionalism (NATPRO) project (Pounds, in review). NATPRO training is expected to improve air traffic safety and efficiency by increasing the controller's attention and perception skills. The training consists of a knowledge-based seminar followed by a practicum designed to enhance a specific skill, for example, *detection of relevant information while scanning*. Although the skill itself is generic, the specific job application is associated with radar scanning in the en route and terminal radar environments and scanning for aircraft, vehicles and pedestrians from the tower. The strength of NATPRO training is that participants receive immediate feedback on their performance relative to their individual baseline performance and can request feedback about their performance relative to the performance of other participants.

Returning to the system level of analysis, one of the major contributions of HFACS is the labeling (thus removing the mystery) of the more common types of latent errors (Reason, 1990). However, it is one thing to know that a particular latent error exists within the system, but that does not tell us the probability that a given latent error might occur. It would be useful to develop probability estimates for the occurrence of each type of latent error so that an overall OE risk assessment could be assigned, e.g., to a given ATC facility, a specific sector, or particular runway. Considering that ASHRAM was derived from human reliability risk assessment, the thought of integrating HFACS into an ASHRAM-like framework has great appeal.

The existing OE investigation process could be further refined to better identify human error mechanisms related to OEs. A revised Form 7210-3 could then be used to record unsafe or contributing actions associated with OEs. Finally, for each ATC position (e.g., radar control or local control) the context could be specified. Having all three components in place, the final step would be to derive an overall risk assessment described previously for a given facility, sector, runway, and so on. Although the mathematics involved in computing a risk assessment are beyond the scope of this paper, the HRA literature provides the necessary guidance for completing such a project (c. f. Swain & Guttmann, 1983).

CONCLUSION

HFACS proved to be a useful taxonomy for classifying the causal factors associated with OEs. A greater percentage were classified as skill-based errors as compared to decision errors. In addition, our results demonstrated that the "causal factors" listed in the current OE reporting system is lacking in information concerning organizational factors, unsafe supervisory acts, and the preconditions of unsafe acts. It is recommended that greater attention be placed on developing a more comprehensive human factors assessment of OE causes across all levels.

As with any study, when interpreting these results, one should consider the quantity and quality of the OE data available. Any post hoc analysis depends on the comprehensiveness and accuracy of the data. In this study we did not distinguish between facility types, i.e., Air Traffic Control Towers (ATCTs), Terminal Radar Approach Control facilities (TRACONs), or Air Route Traffic Control Centers (ARTCCs). Also, we did not examine the causal factors based on who was deemed to be primarily responsible for the OE versus who played a contributing role. We also used only a subset of the data from the 7210-3.

Since the nature of this study was to identify a candidate taxonomy or model and then to test the strongest candidate using OE data, the above limitations do not weaken the conclusion that HFACS, or some variation of it, could profitably be incorporated into the OE reporting process. However, for those who wish to draw additional conclusions from the material presented, the above limitations should be considered.

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APPENDIX A

HFACS Categories and Definitions (Wiegmann & Shappell, 2003).

Unsafe Acts – Performed by the operator

Errors – The mental or physical activities of individuals that fail to achieve their intended outcome

Skill Based – Basic skills that occur without significant conscious thought

Decision – Intentional behavior that proceeds as planned, yet the plan itself proves inadequate or inappropriate for the situation. This is sometimes referred to as "honest mistakes"

Perceptual – Occurs when one's perception of the situation differs from reality usually because of degradation of sensory input

Violations – Willful disregard for the rules and regulations

Routine – Habitual by nature and often tolerated by governing authority

Exceptional – Isolated departures from authority not necessarily indicative of an individual's behavior pattern, nor condoned by management

Preconditions for Unsafe Acts - Addresses the underlying causes for Unsafe Acts

Environmental Factors – Surrounding conditions affecting the operator

Physical Environment – Refers the operational environment and the ambient environment

Technological Environment – Encompasses a variety of issues including the design of the equipment and controls, display/interface characteristics, checklist layouts, task factors and automation

Condition of Operators – Factors within the individual that interferes with optimal performance

Adverse Mental States – Preexisting mental states (such as mental fatigue, personality traits, pernicious attitudes, and misplaced motivation) affecting performance

Adverse Physiological States - Those medical or physiological conditions that preclude safe operations

Physical/Mental Limitations – Those instances when operational requirements exceed the capability of the individual

Personnel Factors – Factors that individuals do to themselves to create preconditions for unsafe acts

Crew Resource Management – Addresses factors that lead to poor coordination among personnel

Personal Readiness – Addresses situations when individuals fail to prepare physically or mentally for duty

Unsafe Supervision – Supervisory actions that influence the conditions of the operator and the type of environment in which they operate

Inadequate Supervision – Deals with lack of guidance and oversight in day-to-day operations

Planned Inappropriate Operations – Occurs when individuals are put in an unacceptable risk due to the operation tempo and/or scheduling of work

Failure to Correct Problem – Those instances when efficiencies among individuals, equipment, training, or other related safety errors are "known" to the supervisor, yet are allowed to continue unabated

Supervisory Violations – Those instances when existing rules and regulations are disregarded by supervisors

Organizational Influences – Fallible decisions of upper-level management affecting supervisory practices as well as the conditions and actions of the operator

Resource Management – Encompasses the realm of corporate-level decision-making regarding the allocation and maintenance of organizational assets (such as personnel, money, equipment, and facilities)

Organizational Climate – The working atmosphere within the organization which includes culture, policies, and structure

Organizational Process – Refers to corporate decisions and rules that govern the everyday activities within the organization. This includes the establishment/ use of standard operational procedures, and formal methods for maintaining oversight of the workforce

APPENDIX B

Probability Risk Assessment, Human Reliability Analysis and ATHEANA

A Technique for Human Error Analysis (ATHEANA) belongs to the class of human reliability analysis (HRA) models used in probabilistic risk assessments (PRAs) to assess the "implications of various aspects of human performance on risk" (Cooper, et. al., 1996, p. 1-1). Closely tied to the nuclear industry, the concept of PRA was developed as a means to: (1) identify potential areas of risk and indicate how those risks could be mitigated, and (2) quantify the overall risk potential of a given plant (Reason, 1990). Both criteria were necessary to achieve public and government support for the building and operating of a nuclear power plants.

As a guideline, the basic steps for conducting a PRA were formally proposed in a 1975 publication of the U.S. Reactor Safety Study known as WASH-1400 (Yellin, 1976). Reason (1990) summarized the PRA steps reported in WASH-1400 as:

a. Identify the sources of potential hazard.
b. Identify the initiating events that could lead to this hazard.
c. Establish the possible sequences that could follow from various initiating events using event trees.
d. Quantify each event sequence. This involves data or judgment about two things: (1) the frequency of the initiating event, and (2) the probability of failure on demand of the relevant safety systems.
e. Determine the overall plant risk. This will be a function of the frequency of all possible accident sequences and their consequences (p. 219)

Although PRAs provided essential information for assigning risk to a proposed nuclear power plant, they failed to adequately address the human element association with system failures (Reason, 1990). Specifically, the means by which probabilities were assigned to potential human failures lacked methodological rigor. Hence a need arose to incorporate a Human Reliability Analysis (HRA) into PRAs.

HRA is defined as a set of methods that assess the probability that a person will correctly perform some system-required activity during a given time period without performing any extraneous activity that can degrade the system (Hollnagel, 2002). One of the more widely used methods of conducting a HRA is the Technique for Human Error Rate Predictions, THERP (Swain & Guttmann, 1983). The procedures used by THERP are similar to those used in a standard PRA and include:

a. Identify the system functions that may be influenced by human error.
b. Conduct a detailed task analysis of the related human operations.
c. Estimate the relevant error probabilities using a combination of subject matter experts (SMEs) and empirical data.
d. Estimate the effects of human errors on system failure events usually by integrating HRA with PRA.

Although widely used, Reason (1990) notes that THERP is often criticized for its simplistic view of the human operator. THERP, as with other HRA techniques, assumes that the human operator behaves as any other piece of equipment. That is, the operator either performs correctly or does not. This assumption is embedded in the basic formula used to calculate the probability of a specific erroneous action (P_{EA}):

$$P_{EA} = HEP_{EA} * \sum_{k=1}^{N} PSF_k * W_k + C$$

where: HEP_{EA} = the human error probability of a erroneous action

PSF = a performance shaping conditions
W = weight of a PSF
C = constant
N = number of PSFs

As Hollnagel (2000) explains, the above equation contains two fundamental assumptions, neither of which is reasonable:

1) First, that the probability of failure can be determined for specific types of actions independently of any context.
2) Second, that the effects of the context are additive, which is the same as saying that the various performance conditions (such as interface quality, stress, level of training, complexity of task, etc.) do not influence one another (p. 2).

Further criticisms of HRA techniques emerged throughout the 1980s. The major criticisms were summarized by Doughtery (1990) and latter elaborated upon by Hollnagel (2002) as follows:

a. Existing empirical data are insufficient to support quantitative predictions of human performance in complex systems. This problem had actually been recognised by HRA practitioners since the early 1960s. As alternatives to empirical data, HRA often relied on either expert judgement or data from simulator studies.
b. Expert judgements can be used *in lieu* of empirical data, but there is a lack of agreement about the use of expert judgement methods. The methods neither have satisfactory between-expert consistency, nor produce accurate predictions.
c. Data from simulator studies can be used instead of empirical data, but the calibration to real life situations or ability to generalize is inadequate. The veracity and validity of simulator data have not yet been convincingly demonstrated.
d. The accuracy of predictions from HRA methods is debatable and generally unproven, particularly for non-routine tasks. Benchmark studies usually produce divergent results, for many different reasons.
e. The psychological realism in most HRA methods is inadequate, and the assumptions about human behaviour are often highly questionable from a psychological point of view.
f. The treatment of important Performance Shaping Factors is inadequate. In particular, there is too little emphasis on PSFs relating to management, organisation, culture, etc. (p. 2)

Given the mounting criticisms surrounding the method of calculating human reliability probabilities, researchers began developing more comprehensive HRA models, such as: A Technique for Human Error Assessment Early in Design, THEA (Pocock, Wright, and Harrison, 1999); Dynamic Reliability Technique for Error Assessment in Man-Machine Systems, DREAMS (Cacciabue, 1993); and the Technique for Human Error Analysis, ATHEANA (Cooper et al., 1996). The latter will be discussed in more detail.

The goal of the ATHEANA project was to develop an improved method for HRA that would "allow for a more realistic assessment and representation of the human contribution to plant risk, and thereby increase the utility of PRA" (Cooper et al., 1996, p. ix). Specifically, ATHEANA was developed to address deficiencies in HRA approaches by:

1. Addressing errors of commission and dependencies
2. Representing more realistically the human-system interactions that have played important roles in accident response, as evidenced by operating experience, and
3. Integrating recent advances in psychology with engineering, human factors and PRA disciplines (Cooper et al., 1996, p. 1-2).

The above were accomplished through an integration of retrospective analysis of past operating events and the prospective analysis in support of PRA. This can be seen in the six elements comprising ATHEANA as shown below. The six elements fall under three broad categories consisting of:

1. Error Forcing Context (EFC)
    a. Performance Shaping Factors (PSF)
    b. Plant Conditions (PC)
2. Human Error
    a. Error Mechanisms
    b. Unsafe Actions
3. PRA Model
    a. Human Failure Events (HFEs)
    b. Scenario Definitions

EFC represents the interaction of PC and PSF. Typically EFCs are unanalyzed plant conditions (similar to Reason's latent errors) that serve to shape an operator's response to an event. Examples of unanalyzed plant conditions are the effects of a history of false alarms associated with a system component, shutting off safety functions during various phases of system shut down, and unusual or incorrect equipment configuration that is integrated into the operating system. Examples of performance-shaping factors include such factors as procedures, training, communications, supervision, staffing, organizational factors, stress and environmental conditions.

ATHEANA defines human error as the "divergence between an action actually performed and the action that should have been performed" (Cooper et. al., 1996, p.2-9). Although the term "action" implies a behavioral act (i.e. unsafe actions), ATHEANA also allows for error mechanisms (i.e., psychological mechanisms such as judgment and decision making) to be incorporated into the definition of human error.

The PRA model is based on probability estimates for the frequency of occurrence of specific failure points associated with a given accident scenario. HFEs represent the failure of a function, system or component as the result of an unsafe action by the human operator (e.g. errors of commission and errors of omission) that places the operation in a worse condition. The scenarios that are used to develop probability estimates usually consist of event tree and fault tree sequences that model a particular chain of events. The level of detail presented depends of the function, systematic, or component level of analysis.

APPENDIX C
Form 7210-3

Final Operational Error/Deviation Report	Report Number _____

Part II. FACILITY MANAGER ACTION

67. Select the category of the operational error/deviation. (more than one category may be possible)

☐ Procedural ☐ Equipment ☐ ATCS ☐ Manager/Supervisor/Other Personnel

68. Causal Factors	***No***	**Yes (employee)**				
		A	**B**	**C**	**D**	**E**
A. Data Posting	☐					
(1) Computer Entry	☐					
Incorrect input		☐	☐	☐	☐	☐
Incorrect update		☐	☐	☐	☐	☐
Premature termination of data		☐	☐	☐	☐	☐
Input/Update not made		☐	☐	☐	☐	☐
Other (explain)		☐	☐	☐	☐	☐
(2) Flight Progress Strip	☐					
Not updated		☐	☐	☐	☐	☐
Interpreted incorrectly		☐	☐	☐	☐	☐
Posted incorrectly		☐	☐	☐	☐	☐
Updated incorrectly		☐	☐	☐	☐	☐
Premature removal		☐	☐	☐	☐	☐
Other (explain)		☐	☐	☐	☐	☐
B. Radar Display	☐					
(1) Misidentification	☐					
Failure to reidentify aircraft when the accepted target identity becomes questionable		☐	☐	☐	☐	☐
Overlapping data blocks		☐	☐	☐	☐	☐
Acceptance of incomplete or difficult to correlate position information		☐	☐	☐	☐	☐
Other (explain)		☐	☐	☐	☐	☐
(2) Inappropriate Use of Displayed Data	☐					
MODE C		☐	☐	☐	☐	☐
BRITE		☐	☐	☐	☐	☐
Conflict alert		☐	☐	☐	☐	☐
Failure to detect displayed data		☐	☐	☐	☐	☐
Failure to comprehend displayed data		☐	☐	☐	☐	☐
Failure to project future status of displayed data		☐	☐	☐	☐	☐
Other (explain)		☐	☐	☐	☐	☐
C. Aircraft Observation (Towers Only)	☐					
(1) Actual Observation of Aircraft		☐	☐	☐	☐	☐
(2) Improper Use of Visual Data	☐					
Landing		☐	☐	☐	☐	☐
Taking Off		☐	☐	☐	☐	☐
Ground Operation	☐					
Taxiing across runway		☐	☐	☐	☐	☐
Holding in position for takeoff		☐	☐	☐	☐	☐
Other (explain)		☐	☐	☐	☐	☐

	No	Yes (employee)				
		A	B	C	D	E
D. Communication Error	☐					
(1) Phraseology		☐	☐	☐	☐	☐
(2) Transposition		☐	☐	☐	☐	☐
(3) Misunderstanding		☐	☐	☐	☐	☐
(4) Read back	☐					
Altitude		☐	☐	☐	☐	☐
Clearance		☐	☐	☐	☐	☐
Identification		☐	☐	☐	☐	☐
Other (explain)		☐	☐	☐	☐	☐
(5) Acknowledgement		☐	☐	☐	☐	☐
(6) Other (explain)		☐	☐	☐	☐	☐
E. Coordination	☐					
(1) Area of Incident	☐					
Intra-sector/position		☐	☐	☐	☐	☐
Inter-sector/position		☐	☐	☐	☐	☐
Inter-facility		☐	☐	☐	☐	☐
Facility type: , level: , and facility ID:		☐	☐	☐	☐	☐
(2) Failure to utilize/comply with precoordination information		☐	☐	☐	☐	☐
(3) Improper use of information exchanged in coordination	☐					
Aircraft Identification		☐	☐	☐	☐	☐
Altitude/Flight Level		☐	☐	☐	☐	☐
Route of Flight		☐	☐	☐	☐	☐
Speeds		☐	☐	☐	☐	☐
APREQs		☐	☐	☐	☐	☐
Special Instructions		☐	☐	☐	☐	☐
Other (explain)		☐	☐	☐	☐	☐
(4) Failure to coordinate between ground and local control	☐					
Crossing active runway		☐	☐	☐	☐	☐
Vehicle, equipment, or personnel on active runway		☐	☐	☐	☐	☐
Use of other than active runway for arrival and departures		☐	☐	☐	☐	☐
Runway closure		☐	☐	☐	☐	☐
Other (explain)		☐	☐	☐	☐	☐
F. Position Relief Briefing	☐					
(1) Employee did not use position relief checklist		☐	☐	☐	☐	☐
(2) Employee being relieved gave incomplete briefing		☐	☐	☐	☐	☐
(3) Relieving employee did not make use of pertinent data exchanged at briefing		☐	☐	☐	☐	☐
(4) Other (explain)		☐	☐	☐	☐	☐

FORM 7210-3 DEFINITIONS

SECTION A: DATA POSTING

A data posting error is any error of calculation, omission, or incomplete data, erroneous entries, handling, or subsequent revisions to this data. This includes errors in posting and recording data. It does not include errors involved in receiving, transmitting, coordinating, or otherwise forwarding this information. If one of the causal factors listed does not adequately describe the factor involved, list the factor under "Other" and provide a brief explanation.

SECTION B: RADAR DISPLAY

a. Misidentification

Radar misidentification means a failure to properly identify the correct target and includes subsequent errors committed after the original identification was properly accomplished. Indicate the listed item(s), which most closely describes the reason for misidentification. If one of the causal factors listed does not adequately describe the factor involved, list the factor under "Other" and provide a brief explanation.

b. Inappropriate Use of Displayed Data

A data or display information error occurs due to a failure to maintain constant surveillance of a flight data display or traffic situation and to properly use the information presented by the display or situation. If one of the causal factors listed does not adequately describe the factor involved, list the factor under "Other" and provide a brief explanation.

SECTION C: AIRCRAFT OBSERVATION (Towers Only)

An aircraft observation error means a failure to maintain constant surveillance of aircraft and the movement area, and to properly react to, interpret, or otherwise utilize, in a timely manner, the information being viewed. If one of the causal factors listed does not adequately describe the factor involved, list the factor under "Other" and provide a brief explanation.

SECTION D: COMMUNICATIONS ERROR

A communications error is a causal factor associated with the exchange of information between two or more people (e.g., pilots and specialists). It refers to the failure of human communication not communications equipment.

a. Phraseology

Use of incorrect or improper phraseology.

b. Transposition

An error due to transposition of words, numbers, or symbols by either oral or written means. This involves writing/saying one thing while thinking/hearing something else.

c. Misunderstanding

The failure to communicate clearly and concisely so that no misunderstanding exists for any actions contemplated or agreed upon.

d. Read back

The failure to identify improper or incorrect read back of information.

e. Acknowledgment

The failure to obtain or give an acknowledgment for the receipt of information.

f. Other

If the causal factors listed above do not adequately describe the factor involved, list the factor and provide a brief explanation.

SECTION E: COORDINATION

Any factor associated with a failure to exchange requirement information. This includes coordination between individuals, positions of operation, and facilities for exchange of information such as APREQ's, position reports, forwarding of flight data, etc. If one of the causal factors listed does not adequately describe the factor involved, list the factor under "Other" and provide a brief explanation.

SECTION F: POSITION RELIEF BRIEFING

Relief briefing errors are special errors of both communication and coordination, which occur as the result of position relief. They include such things as failure to give a relief briefing, failure to request a briefing, incomplete or erroneous briefing, etc. If one of the causal factors listed does not adequately describe the factor involved, list the factor under "Other" and provide a brief explanation.